Urban pluvial flooding : development of GIS based pathway model for surface flooding and interface with surcharged sewer model

Inondations pluviales urbaines : développement d'un modèle d'inondation de surface basé sur un SIG et interface avec un modèle de réseaux en charge

Boonya-aroonnet S[1], Maksimović Č[1], Prodanović D[2], Djordjević S[3]

[1]Urban Water Research Group, Dept. of Civil & Environmental Engineering, Imperial College London, London SW7 2AZ, UK.
Email: s.boonya@imperial.ac.uk ; c.maksimovic@imperial.ac.uk

[2]Institute for Hydraulic and Environmental Engineering, Faculty of Civil Engineering, University of Belgrade, Serbia.
Email: eprodano@hikom.grf.bg.ac.yu

[3]Centre for Water Systems, University of Exeter, Exeter EX4 4QF, UK.
Email: s.djordjevic@ex.ac.uk

RESUME

Ces travaux visent à améliorer le modèle de ruissellement de surface utilisé pour modéliser les inondations pluviales urbaines grâce au concept de «l'assainissement-dual» (interfaces dynamiques entre un modèle de réseaux et un modèle de ruissellement de surface). L'outil SIG développé utilise des données haute résolution DTM/DEM collectées par la technique LIDAR. Ainsi on augmente de façon novatrice la performance du modèle, notamment pour l'analyse détaillée du ruissellement de surface (ex. la rétention de surface, la formation d'étang, les chemins préférentiels de l'écoulement de surface, et sa capacité d'assainissement). Les résultats de ce projet rendent possible une gestion de pointe des crues urbaines en temps réel par l'amélioration du contrôle et aussi à court terme en matière de prévision des pluies et des crues.

ABSTRACT

This paper presents the work on development of overland flow model for urban pluvial flooding under the "dual-drainage" concept where 1D sewer flow dynamically interacts with 1D overland flow. This is the case during heavy storms when the capacity of sewer system is exceeded, system becomes surcharged and flow over terrain occurs. The developed GIS tools use the emerging technology of high-resolution DTM/DEM data collected by LiDAR technique. This gives a new possibility to enhance model's capacity especially for detailed analysis of overland flow (e.g. surface retention, pond forming, preferential pathways of surface runoff, and its drainage capacity). Completion of this development enables opening up of several new areas of advanced urban flood management that includes improvement in real-time control, improvement of links with rainfall now-casting, and short term urban flood forecasting.

KEYWORDS

Flood modelling ; overland flow ; storm sewer pluvial flooding ; urban drainage.

1 INTRODUCTION

Urban flooding is currently one of the major and costly environmental hazards. In order to minimise the risk from flood events, improvement in prediction and quantification of the flood risk is needed.

Conventional urban drainage models deal with rainfall-runoff analysis under the effects of local storms. Recently, an integrated approach of various models (Mark and Parkinson, 2005; Schmitt et al., 2004) is commonly employed and the use of sophisticated hydraulic models as diagnostic, design and decision-support tools has become standard practice in water industry. There has also been significant progress in wrapping urban drainage models in the sophisticated interfaces, linking them with GIS (Geographical Information Systems) and adding elaborate optimization techniques (Lhomme et al., 2004). In addition, results presented recently by Ball and Alexander (2006) and Vojinović et al. (2006) contribute to general understanding of some aspects of flooding process.

However, concerns raised by Maksimović and Prodanović (2001) have not been addressed yet, to realistically model the overland flow that takes place during heavy storms, when water can flow into and from the underground sewer network, along streets (as primary preferential paths), but also can create surface ponds and flow across the urban catchment (preferential paths different from streets). Fortunately, the emerging technology of the high-resolution DTM (Digital Terrain Model) and DEM (Digital Elevation Model) e.g. LiDAR (Light Detection And Ranging) makes a detailed analysis of overland flow achievable, although further work is still needed in developing this technological advance in the context of urban flood management. Conventional model concepts are not suitable for those newly available features. This in fact opens a new possibility to enhance model's capacity for the next generation of urban flood modelling beyond the limitations reported by Mark et al., (2004).

This paper presents recent progress in modelling of overland flow in urban environment caused by pluvial flooding, originally initiated by Prodanović (1999) and Djordjević (2001). The concept is based on GIS-centred analysis of the "conditioned" DTM/DEM so that the features of the catchment crucial for identification of flood vulnerable areas (mainly ponds) are derived and the geometric characteristics of the preferential paths computed. Realistic modelling of overland flow coupled with buried (sub-surface) network is then enabled by applying physically based surface runoff modelling concept developed by Maksimović and Radojković (1986). A set of GIS modules defining various phases of overland flow and its interactions with time dependent water bodies creating ponds and computational (and physical) inlets to sewer network has been developed and tested. The paper describes the concept, modelling process, testing and trial application in a selected case study (Bishopbriggs, Glasgow, UK) in which severe urban flood took place in 2002.

2 MAIN OBJECTIVES

The overall objective is to develop the GIS-based tool for analysis of surface runoff in urban areas, to enable reliable dynamic modelling of pluvial flooding by linking it to the SIPSON model (Djordjević et al., 2005) and by testing it against the data available from a selected case study, Bishopbriggs, Glasgow. This objective is achieved by performing detailed tasks, as follow :

- DTM enhancement: DTM has to be "hydraulically" correct i.e. without data noise that will induce pits and flat areas and with correct directions of slopes. Data reduction is also needed to reduce the number of points when LiDAR raster data are used as a source of DTM data.

- Identification of the spots susceptible to flooding: Depressions or ponds need to be located and their stage-volume curves should be created. These ponds are possible “candidates” vulnerable to flooding.
- Connectivity analysis: Mapping of connection links, i.e. preferential flow paths, connection of natural surface pathways between pond candidates, connection of surface flow paths and manholes (interface between surface and underground system).
- Geometry approximation of the connection links: The suitable prismatic shape of channel cross-section should be determined for the identified paths based on the high quality DTM in order to model the routing of the surface water.

Finally, the outputs of the overland flow elements are to be introduced into the model for simulation of interactions of the overland and pipe flows. The approach is 1D/1D (i.e. one-dimensional in both overland and pipe flow). An upgraded surface pathway network consists of storage nodes (with its characteristics) and links (with its shapes).

3 MODEL DEVELOPMENT

3.1 Pluvial urban flooding

Pluvial flooding is caused by extreme local storms. In order to model urban pluvial flooding reliably it is necessary to realistically represent urban fabric (or cover), both land use and terrain, in its full complexity. Having such data, the physically based concept can be implemented in both surface and sewer network part of the system and the interaction of these two systems can be analysed throughout the storm event. Critical phase usually occurs when the sewer network’s capacity is exceeded: some parts of the network become surcharged and flow through the inlets may change the direction (Fig 1–case c). In extreme cases (heavy storms) pluvial flooding can take place even if the sewer network is with free-surface flow.

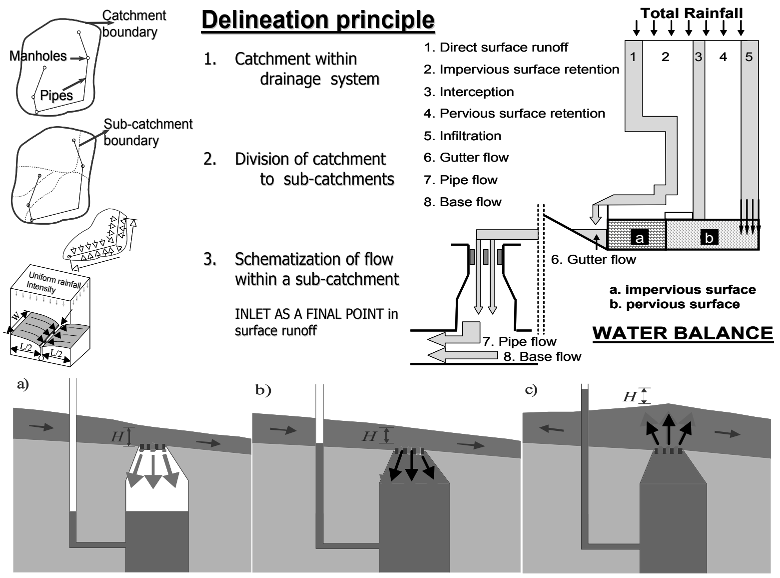

Figure 1. Physically based modelling surface runoff and phases in surcharged pipes (Top left: urban catchment is delineated in small sub-catchments, Top right: all components of water balance, Lower: flow in the inlets interact with overland flow throughout storm event)

3.2 Physically based modelling

Traditional "conceptual model" methods of analysis such as rational formula, time of concentration, linear reservoirs, regression analysis etc. fail in representing full dynamics of urban catchment and flood processes. In physically-based modelling approach water movement over the surface is modelled by solving the appropriate approximation of mass and momentum conservation equations. That allows modellers to simulate features of urban areas more realistically. This includes dynamics of the processes in temporary surface retention (ponds) and flow across the urban catchment along preferential pathways, see Fig 2. Solving these processes has become essential requirement in a new generation of urban flooding models.

To improve overland flow modelling the following tasks are carried out: i) automatic sub-catchment delineation in order to identify sub-area that contributes the flow to individual drainage elements through inlets based on the terrain slope (so called DTM based sub-catchment delineation); ii) identification of flood vulnerable spots i.e. locating the surface retention ponds in the urban catchment and quantification of their areas/volumes; iii) generation of links (surface pathways) between ponds and manholes; and iv) estimation of suitable geometry for surface pathways to route the overland flow movement. Finally, when underground network is surcharged, the surface flow is generated and it is routed by the full dynamic St.Venant equations. In the above considerations, two types of surface retention are to be distinguished: a) small scale (micro) surface retention which affects water balance and which is normally applied in most contemporary storm drainage models (to produce effective rainfall); b) macro retention of the net rainfall in large depressions, which is the unique feature of the model presented in this paper.

3.3 DTM analysis

Performance and reliability of surface overland flow model is highly dependant on quality and resolution of DTM. Physical processes such as surface flow, surface retention, and surface conveyance along preferential pathways are essential elements in modelling of urban flooding. These require high quality of terrain data e.g. DTM with horizontal resolution finer than 5m (in order for the urban features such as streets to be properly described) and 5cm vertical accuracy. Additionally, land-use maps are essential to locate streets and building and other features which influence routes and directions of surface runoff.

Obviously, the quality of DTM is essential. Imperfection of DTM could lead to unfavourable results of surface runoff analysis. The original DTM may contain the noise (from different sources) which will create severe problems in pathway delineation. The major task is to correct and smoothen the DTM. There is yet no standard and general way how to do that, so special attention is required for each particular issue.

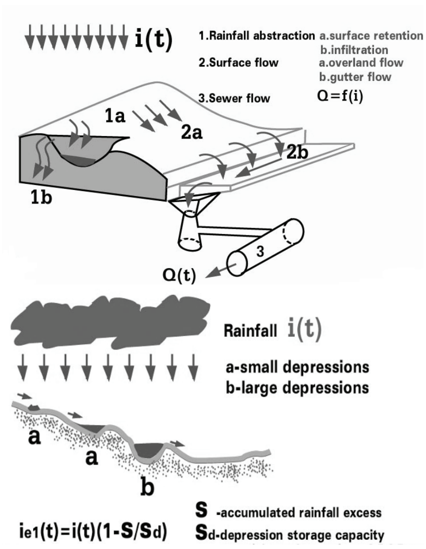

Figure 2. (Top) Flow processes in urban drainage system and (Below) surface retention of schematised surface (overland) flow in urban areas

3.4 Identification of flood vulnerable areas

In most cases, flood occurs when surface runoff combined with surcharged water from drainage system flows along the natural preferential paths (including streets) and accumulates in local depression (pond). Depressions may not be apparent during “regular” storms when water flows to sewer network without creation of ponds. However when the “absorption capacity” of the network is exceeded, ponds are created naturally. Ponds have their own dynamics, they can be isolated or mutually connected and their flow pattern is function of flooding and it changes in time. The flood vulnerable areas are identified and quantified by DTM analysis.

3.5 Definitions of hydraulic relationships for ponds, preferential paths and links

During urban pluvial flooding, when the capacity of drainage system (minor system) is exceeded, water flows over the surface along flood pathways (major system). The major system may consist of existing roads and walkways that are lower than surrounding areas, and tend to accumulate in natural or man-made depressions on the ground. Such flood pathways can transfer water over significant distances so that flooding can occur at locations remote from the point of discharge from the drainage system. Surface runoff from adjacent areas that have no direct connection to the sewer network is also known to contribute to the overland flow.

3.6 Software development and sensitivity issues

Overland flow subsystem is organised in a series of modules that deal with DTM analysis, data preparation, input to models, hydrodynamic models, post processing and graphical (GIS-based) presentation of results. All the processes are data quality sensitive. These issues and results are going to be presented elsewhere.

4 DEVELOPED GIS TOOLS

4.1 Flood vulnerable areas

Flood vulnerable areas are usually located in the local depressions (ponds) as the overland flow tends to accumulate there. In our case, DTM raster image was employed to analyse flood vulnerability and entire dynamic process. Algorithm begins with looking for the locally lowest points in entire DTM and marks them as potential sinks. Additional flood vulnerable spots from historical, documented floods could also be used. However, in most cases, all local depressions would cover the potential flood areas. Based on the DTM, pond boundary will be delineated for each identified lowest points with the natural exit point as the termination criteria (see Fig 3–left). Occasionally, the algorithm would identify small ponds possibly originating from the noise or imperfection of DTM. Additional analysis is required to determine suitable “threshold volume” to filter out those small ponds. However, if those ponds have significant contributing areas, they cannot be ignored.

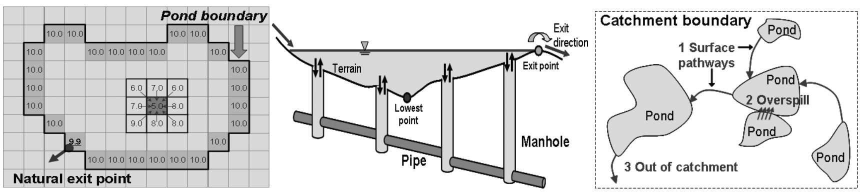

Figure 3. (Left) Pond delineation algorithm starts with the lowest point in the DTM (numbers are elevations); (Mid) interaction with buried drainage network; and (Right) pond connectivity calculated from DTM.

4.2 Connectivity analysis and interactions

Flood water originating from surface runoff or from surcharged network flows over land and accumulates in depressions. Apparently, once the top level of depression is reached, water will either overflow to the neighbouring depression (overflow case) or will flow superficially along (connecting) preferential paths until it reaches the next depression or inlet to the sewer network. The algorithm for creating the connectivity (Fig 3–right) e.g. surface pathways or overspill (spillway) between ponds is developed by “rolling ball” technique. From the natural exit points, the analysis determines pathways by preferential flow directions based on terrain slope but also by taking into account presence of buildings and other features of urban fabric. This represents the reality of the surface overland flow process and ensures essential requirement of reliable modelling.

4.3 Estimation of pathway geometry

Modelling of surface flow of floodwater requires additional information e.g. the shape of the surface drainage open-channel, the upstream/downstream elevations, roughness, and actual length between two ponds or surface nodes (presented in Fig 4). The suitable shapes of pathways are determined using cross-sections of surrounding DTM along the paths. The averaged flow areas at different depths are calculated and the proper shape was selected to fit this depth-flow areas curve. Users can choose the final output to be arbitrary or trapezoidal cross-sections (Fig 4d).

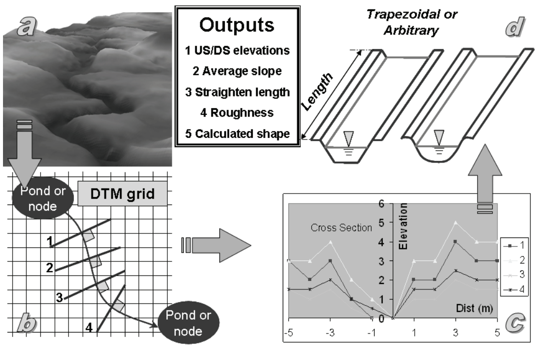

Figure 4. Estimation of surface pathway geometry

4.4 Integration and implementation

Based on the dual-drainage model, all GIS modules are developed in order to prepare the surface network and its interaction with sub-surface network. Finally, they are integrated into methodological framework for advanced modelling of urban pluvial flooding, as shown in Fig 5. The major system represents the surface network (ponds and preferential paths including streets) and the minor system represents the sewer network. For each system the automatic algorithm will generate two sets of simulation inputs i.e. the network (nodes & links) and parameters for rainfall-runoff model (e.g. sub-catchment areas, percentage of pervious and impervious covers).

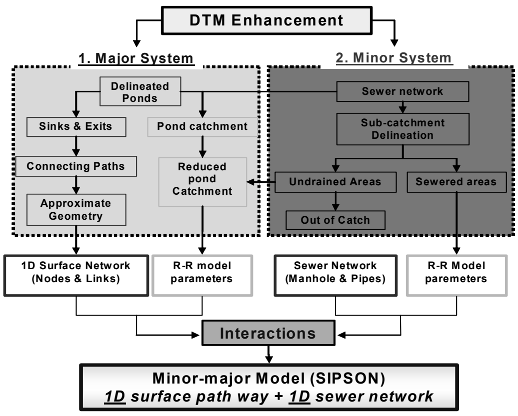

Figure 5. The modelling framework for advanced modelling of urban pluvial flooding

4.5 Issue of 1D/1D and 1D/2D modelling approaches

Alternatively, a higher level of modelling details for surface overland flow can be achieved using 1D/2D models available most recently, in which a 1D sewer network model is coupled with a 2D surface flow model (Carr and Smith, 2006; Chen et al., 2005). Interactions between the two models take place between underground network nodes and surface computational grid cells. Obviously, this approach enables much more realistic analysis of overland flows than the 1D/1D approach, especially in extreme events in which flood flows are not confined to street/road profiles or identified preferential pathways. Also, treatment of buildings is more exact. However, 2D models are even more sensitive on accuracy of DTM data, require small time steps and are computationally very demanding and as such still inadequate for real-time representation or quick forecasting of the flooding process.

5 CASE STUDY

The proposed modelling approach was tested with the selected catchment of Bishopbriggs, Glasgow, where the severe flood occurred in 2002 (Fig 6). Outflow from the surcharged sewer network is clearly visible in the left photograph.

Figure 6. Photographs from Glasgow 2002 severe flood

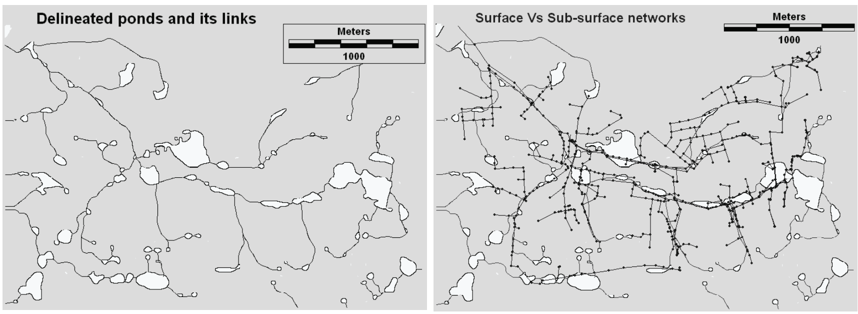

Figure 7. Generated surface network (left); sewer system and overlaid surface network (right)

Analysis of the causes of the this flooding event has been carried out by Wilson (2003), who identified major “stakeholders” and their potential “contributions” and who kindly provided photographs in Fig 6. Detailed analysis of LiDAR based DTM provided by InfoTerra has been used for creation of the network of ponds and preferential paths shown in the left of the Fig 7. When superimposed on the storm sewer network, it can be noticed that significant part of preferential paths does not coincide with streets (sewer pipes). The results of hydrodynamic simulations of the 2002 flood will be presented in the conference.

6 CONCLUSIONS

The paper has presented an innovative method for analysis of overland flow component during pluvial flooding in urban areas. The concept is based on the usage of detailed high quality DTM, from which the surface network of ponds and preferential paths between manholes are created. The surface network interacts with the underground sewer network. This concept appears to be a breakthrough in this area on the global scale solution of urban flood modelling. This development is supposed to motivate professional software companies to follow this route.

Integration of the overland flow modules with the SIPSON model within one software platform is in progress. Future research will include objective comparison between results obtained by the presented methodology and the coupled 1D/2D models.

The work presented here is the first (though very important) phase in enabling a fully integrated urban pluvial flood to be modelled by the 1D/1D approach. It should be noted that full success in implementation of this concept depends on the progress in improving vertical resolution of DTM in complex urban areas. Completion of this product enables opening up of several new areas of advanced urban flood management including improvements in Real Time Control, improvement of links with rainfall now-casting and development of short term urban flood forecasting.

7 ACKNOWLEDGEMENTS

Financial support by the UKEPSRC and other funding organisations is acknowledged.

LIST OF REFERENCES

Ball, J. E. and Alexander, M. (2006). Modeling street surface runoff. *7th Int. Conf. on Hydroinformatics,* Nice, France, Vol. I, 288-295.

Carr, R. S. and Smith, G. P. (2006). Linking 2D and pipe hydraulic models at fine spatial scales. *7th Int. Conf. on Urban Drainage Modelling and 4th Int. Conf. on Water Sensitive Urban Design,* Melbourne, Vol. 2, V2.361-V2.368.

Chen, A. S., Hsu, M. H., Chen, T. S. and Chang, T. J. (2005). An integrated inundation model for highly developed urban areas. Water Science & Technology, 51(2), 221-229.

Djordjević, S. (2001). *A mathematical model of the interaction between surface and buried pipe flow in urban runoff and drainage*. PhD Thesis, Faculty of Civil Eng., University of Belgrade.

Djordjević, S., Prodanović, D., Maksimović, Č., Ivetić, M. and Savić, D. (2005). SIPSON – Simulation of Interaction between Pipe flow and Surface Overland flow in Networks. *Water Science & Technology,* 52(5), 275–283.

Lhomme, J., Bouvier, C. and Perrin, J. L. (2004). Applying a GIS-based geomorphological routing model in urban catchments. *Journal of Hydrology,* 299(3-4), 203-216.

Maksimović, Č. and Prodanović, D. (2001). Modelling of Urban Flooding - Breakthrough or Recycling of Outdated Concepts. *Specialty Symp. of the World Water and Environmental Resources Congress,* Orlando, Florida.

Maksimović, Č. and Radojković, M. (1986). *Urban Drainage Catchments.* Pergamon Press, Oxford.

Mark, O. and Parkinson, J. (2005). The future of urban stormwater management: An integrated approach. *Water 21,* August 2005, 30-32.

Mark, O., Weesakul, S., Apirumanekul, C., Boonya-aroonnet, S. and Djordjević, S. (2004). Potential and Limitation of 1D Modelling of Urban Flooding. *Journal of Hydrology,* 299(3-4), 284-299.

Prodanović, D. (1999). *Improvement of the methods for the hydroinformatics application in urban runoff analysis* PhD Thesis, Faculty of Civil Engineering, University of Belgrade. (in Serbian)

Schmitt, T. G., Thomas, M. and Ettrich, N. (2004). Analysis and modeling of flooding in urban drainage systems. *Journal of Hydrology,* 299(3-4), 300-311.

Vojinovic, Z., Bonillo, J., Kaushik, C. and Price, R. (2006). Modelling flow transitions at street junctions with 1D and 2D models. 7th Int. Conf. on Hydroinformatics, Nice, France, Vol. I, 377-384.

Wilson, D. (2003). Private communication.